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**MEASUREMENT OF THE IMPETUS, COVOLUME,
AND BURNING RATE OF SOLID PROPELLANTS**

by

J. M. Massey, Jr.

Warhead and Terminal Ballistics Laboratory



**U. S. NAVAL WEAPONS LABORATORY
DAHLGREN, VIRGINIA**

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THE FOLLOWING PAGES ARE CHANGES

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U. S. NAVAL WEAPONS LABORATORY
DAHLGREN, VA.

In reply refer to
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From: Commander, U. S. Naval Weapons Laboratory
Dahlgren, Virginia
To: Holders of NWL Report No. 1872

Subj: NWL, Dahlgren Report No. 1872; changes to

1. Equations (17) and (19) are in error and should read as follows:

$$\frac{dC}{dt} = C_b(a_1 + 2a_2l + 3a_3l^2) \frac{dl}{dt} \quad (17)$$

$$\frac{dl}{dt} = \frac{dP}{dt} / P_{\max}(a_1 + 2a_2l + 3a_3l^2) \quad (19)$$

2. The labeling of Figure 1 is in error. The units of the horizontal axis should be

$$\left(\frac{\text{cm}^2}{\text{dyne}} \times 10^9 \right)$$

and the units of the vertical axis should be

$$\left(\frac{\text{cm}^3}{\text{gm}} \right).$$

3. The next to the last line on page 8 is in error and should read in part "...equations (9), (11), (17), and (19).".

4. The results are considered correct and are not affected by the above changes.

W. E. McKenzie

W. E. McKenzie
By direction

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U. S. Naval Weapons Laboratory
Dahlgren, Virginia

Measurement of the Impetus, Covolume,
and Burning Rate of Solid Propellants

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J. M. Massey, Jr.
Warhead and Terminal Ballistics Laboratory

NWL Report No. 1872
WEPTASK No. RMMO-33-020/210-1/F008-11-001

31 July 1963

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ABSTRACT

A method, using closed vessel techniques, for determining the impetus (force constant), covolume, and burning rate of solid propellant is described. Data obtained by this method are presented for thirteen solid propellants.

FOREWORD

The development of the procedures and experimental work summarized in this report was carried out under WEPTASK No. RMMO-33-020/210-1/FO08-11-001, Problem Assignments 1 and 3. This effort was begun in January 1962 and completed in December 1962.

Paul N. Stamoulas conducted the experimental tests and prepared the inputs for the digital computations. Charles W. Fischler, Jr., of the Computation and Analysis Laboratory prepared the IBM 7090 digital computer program used to calculate the impetuses and burning rates reported herein.

This report was reviewed by the following personnel of the Warhead and Terminal Ballistics Laboratory:

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Technical Director

INTRODUCTION

Ballistic calculations of cartridge actuated devices require the thermodynamic and physical properties of the solid propellant and propellant gases involved. The results of the calculations are usually quite sensitive to changes in the granulation (size and shape), impetus (force constant), and burning rate of the solid propellant. However, the results are insensitive to reasonable changes in the specific heats of the propellant gases and density of the solid propellant. Hence, if reasonable estimates of the device parameters (such as heat loss and friction) are made, meaningful ballistic predictions can usually be made if accurate values for the impetus and burning rate of the solid propellant are available. At extremely high pressures (above 10,000 psi) the propellant gases deviate markedly from an ideal gas. In this region the covolume should not be neglected.

This report describes a method used at the U. S. Naval Weapons Laboratory, Dahlgren, Virginia to obtain the impetus, burning rate, and covolume of solid propellants. The theory upon which the method is based follows closely that given in reference (a).

The results for thirteen solid propellants used in cartridge actuated device applications at the U. S. Naval Weapons Laboratory, Dahlgren, Virginia, are also given.

THEORY AND DISCUSSION

I. Measurements of Impetus and Covolume -

The equation of state of propellant gases contained in a closed vessel may, with sufficient accuracy, be written, (reference (b)),

$$P \left(V_0 + \frac{C}{\rho} + C\eta \right) = C \frac{R}{M} T, \quad (1)$$

where P is the partial pressure of the propellant gases

V_0 is the initial volume available to the propellant gases at ignition

C is the mass of the propellant gases

ρ is the density of the solid propellant

η is the covolume of the propellant gases

R is the gas constant per mole

T is the gas temperature

M is the average molecular weight of the propellant gases

Assumptions regarding this system are:

(a) the quantities P, C and T are time dependent while V_o , ρ , η , R and M are constants.

(b) the final products of reaction of the solid propellant are gases.

(c) mixing of the hot propellant gases with the relatively cool gases present at ignition, such as air and the gases produced by the igniter, is such that the drop in partial pressure of the propellant gases is exactly compensated by the rise in partial pressure of the gases present at ignition. Assumption (a) is equivalent to assuming that η and M are independent of both temperature and pressure; a very good assumption as discussed in Chapter 3 of reference (a). Assumption (b) is actually a requirement for clean burning propellants and is essentially true for the propellants reported here. Assumption (c) is true provided the specific heats and molecular weights of the mixing gases are the same. This is only approximately correct but the error introduced by this assumption is not large since the mass of the original gases is only 1 or 2% of the mass of propellant gases generated. The covolume η is a measure of the volume occupied by the molecules of a unit mass of gas. If C_b is the mass of propellant gas produced at burnout (the time at which all the propellant is consumed), then by assumption (b) above, C_b/ρ would be the volume occupied by the solid propellant prior to ignition. If the mass of original gases present at ignition is I, then the initial volume available to the propellant gases at ignition is given by

$$V_o = V_c - C_b/\rho - I \eta_I \quad , \quad (2)$$

where V_c is the volume of the empty vessel and η_I is the covolume of the original gases. In order to eliminate the temperature T in equation (1) we write the expression of the energy balance of the propellant gases^(a)

$$C C_v (T_v - T) = E_h \quad , \quad (3)$$

where C_v is the heat capacity at constant volume of the propellant gases

T_v is the temperature of the uncooled reaction products of the propellant, also known as the adiabatic constant volume flame temperature

E_h is the heat energy lost by the propellant gases

Solution of equation (3) for T and substitution in equation (1) yields

$$P \left[V_o + C \left(\frac{1}{\rho} - \eta \right) \right] = C \frac{RT_v}{M} - \frac{R}{M C_v} E_h \quad (4)$$

It is to be noted that the slight change in volume and the associated strain energy due to elastic expansion of the closed vessel has been neglected. This is justified because its effect on the pressure is a fraction of a percent and is masked by the uncertainty in E_h .

The impetus (force constant) is defined as

$$F = \frac{R T_v}{M} \quad (5)$$

If we assume that the maximum partial pressure P_{max} is reached at burnout,¹ equations (4) and (5) can be combined to yield

$$P_{max} \left[V_o + C_b \left(\frac{1}{\rho} - \eta \right) \right] = C_b F - \frac{R}{M C_v} E_h \quad (6)$$

Since P_{max} , V_o , C_b and ρ can be measured directly,² equation (6) is sufficient to determine the impetus F and covolume η provided E_h can be determined or made negligible.

¹If heat losses are large P_{max} may occur slightly before burnout.

² P_{max} is not measured directly but is obtained by measuring the total maximum pressure and subtracting the pressure of the original gases in the vessel at ignition. The validity of this method is based on assumption (c) above.

Since no direct accurate method of determining E_h exists, an attempt was made to make E_h negligible by grinding the propellant to granules which would pass a number 30 mesh sieve. This reduced the burning times to less than 10 milliseconds for those cases in which the maximum pressure was sufficiently high, usually 150 bars or more. An attempt was then made to account for the residual heat loss at the time maximum pressure was reached by determining the maximum pressure P'_{max} that would have been obtained if E_h had truly been zero, i.e., if in reality the process had been adiabatic. The assumption was made that extrapolation of the pressure-time curve, from the time after maximum pressure was reached, into the region of time just prior to this would produce a locus of points corresponding to the maximum pressures of rounds requiring less time to consume, but having the same charge weight. If the assumption were completely valid, one could obtain P'_{max} by extrapolating back to the time of ignition and obtain the maximum pressure of fictitious firing having zero burning time and permitting no heat loss up to the time of maximum pressure. Comparison of the maximum pressures of several firings with different burning times demonstrated the assumption yielded a gross over correction for heat loss. It was found, at least for burning times of less than 20 milliseconds, that extrapolation back to a time corresponding to approximately $P_{max}/2$ yielded linear results in accordance with equation (8). This is demonstrated by the linearity of the data shown in Figure 1.

Dropping the E_h term and replacing P_{max} in equation (6) with P'_{max} , we have

$$P'_{max} \left[V_o + C_b \left(\frac{1}{\rho} - \eta \right) \right] = C_b F \quad (7)$$

or, on rearranging,

$$\left(\frac{V_o}{C_b} + \frac{1}{\rho} \right) = F \left(\frac{1}{P'_{max}} \right) + \eta \quad (8)$$

Equation (8) can be fitted by least squares analysis to the data of several firings having different charge weights C_b to obtain the impetus F slope and the covolume η (intercept).

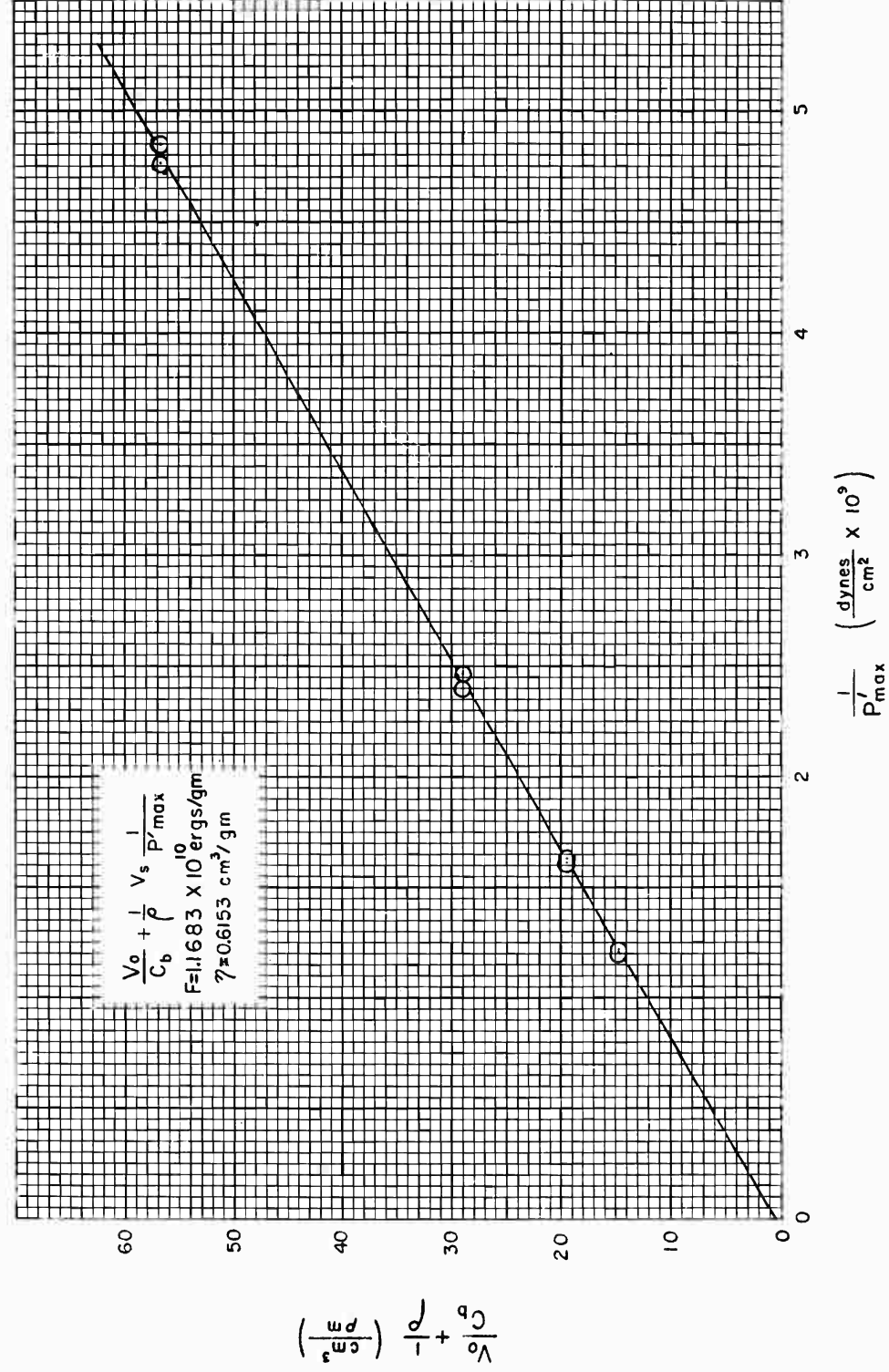


FIGURE 1: TYPICAL PLOT-DATA for DETERMINING IMPETUS-HES 5250.96

II. Measurement of the Burning Rate -

According to Piobert's law (reference (b)), all surfaces of a propellant grain are assumed to recede at equal rates during burning or, in other words, in layers parallel to the initial surfaces. A further assumption is that shortly after ignition the entire surface of the propellant is burning. This is a reasonable assumption based on wide experience with quenched grains and in fitting interior ballistic computations to empirical results. Let ℓ refer to the distance the surface has receded at any time. The linear burning rate is then defined as $d\ell/dt$. The linear burning rate has been found to be a function of the total gas pressure and is usually expressed by

$$\frac{d\ell}{dt} = B \left(P_{\text{total}} \right)^n, \quad (9)$$

where B is a constant coefficient and n is a constant referred to as the burning rate index.

The term P_{total} is used here to mean the total gas pressure as distinguished from the partial pressure P produced by the propellant gases. If P_1 is the pressure produced by the original gases at ignition, then

$$P_{\text{total}} = P + P_1. \quad (10)$$

The mass of propellant burned C can be related to the distance ℓ the burning surface has receded by

$$\dot{C} = C_b \left(a_1 \ell + a_2 \ell^2 + a_3 \ell^3 \right) \quad (11)$$

for most common propellant geometrics such as spheres, solid cylinders, and perforated cylinders.³ Equation (4) may be rewritten to yield

$$P \left[1 + \frac{C}{V_o} \left(\frac{1}{\rho} - \eta \right) \right] = \frac{C}{V_o} \frac{R}{M} \left[T_v - \frac{E_h}{C C_v} \right]. \quad (12)$$

³The Form Function Equation (Equation (11)) is discussed in references (a) and (b).

The calculations are much simpler if the term $C/V_o (1/\rho - \eta)$ is negligible compared to 1. For the work reported here, a typical maximum error of 5% is introduced by neglecting this term. Throughout most of the burning cycle the error is considerably less since it is proportional to the mass of propellant gas produced. With this simplification, equation (12) becomes

$$P = C \frac{R}{V_o M} \left[T_v - \frac{E_h}{C C_v} \right] \quad (13)$$

At burnout $P = P_{\max}$,⁴ $C = C_b$, and $E_h = E_{hb}$ and equation (13) can be written

$$P_{\max} = C_b \frac{R}{V_o M} \left[T_v - \frac{E_{hb}}{C C_v} \right] \quad (14)$$

Upon elimination of T_v from these two equations we have

$$P = C \frac{R}{V_o M} \left[\frac{P_{\max}}{C_b} \frac{V_o M}{R} + \frac{E_{hb}}{C_b C_v} - \frac{E_h}{C C_v} \right] \quad (15)$$

It is known that both E_h and C start at zero and proceed to their respective maximums E_{hb} and C_b during the burning cycle. At least qualitatively, E_h can be considered proportional to C .⁵ If this were true, equation (15) would reduce to

$$P = \frac{C}{C_b} P_{\max} \quad (16)$$

For this work it was assumed that equation (16) was valid. Equation (11) can be differentiated to yield

$$\frac{dC}{dt} = \left(a_1 + 2 a_2 l + 3 a_3 l^2 \right) \frac{dl}{dt} \quad (17)$$

⁴If heat losses are large P_{\max} may occur before burnout.

⁵This assumption is suggested in reference (b). This along with neglecting the term $(C/V_o) (1/\rho - \eta)$, greatly simplifies the calculations and preliminary collection of information required for burning rate determinations in accordance with reference (c).

Differentiation of equation (16) gives

$$\frac{dC}{dt} = \frac{C_b}{P_{\max}} \frac{dP}{dt} \quad (18)$$

Solution of equations (17) and (18) for dl/dt gives the burning rate for any total pressure P_{total} .

$$\frac{dl}{dt} = \frac{C_b}{P_{\max}} \frac{dP}{dt} \left(a_1 + 2 a_2 l + 3 a_3 l^2 \right) \quad (19)$$

The value of l at each total pressure of interest can be obtained by solving equation (16) for C (recalling that $P = P_{\text{total}} - P_1$) and then solving equation (11) for the corresponding value of l . Substituting these values in equation (19) gives the burning rate dl/dt for the corresponding total pressure P_{total} . Equation (9) can be fitted to the burning rate data by least squares analysis to determine the coefficient B and the index n .

EXPERIMENTAL

I. Apparatus -

A cylindrical closed vessel (see Figure 2) of 4130 steel with inside nominal dimensions of 2 inches diameter and 10 inches length sealed at one end with a screw-in cap and "O" ring was used for all firings in determining the impetus and burning rates. The volume of the vessel was 534 cubic centimeters. A Halex ignition cartridge, P/N 2141, was used as an ignition source. A piezoelectric crystal gauge was used to measure the fast rising pressure pulses obtained in the finely ground propellant firings and an "NWL strain gauge" was used to measure the slower rising pressure pulses of the whole grain propellant firings. The piezo gauge was not used for the slower rising pressure pulse because of its tendency to pick up small spurious signals rendering the output trace useless for accurately determining the slope dP/dt of the pressure-time trace required in equation (19). The output of the pressure gauge was recorded on a recording oscillograph.

II. Procedure -

In each closed bomb firing the propellant charge was loaded in a small silk bag and placed directly over the igniter hole. In the case of the whole grain propellant firings, an additional 0.5 gram charge of finely ground propellant of the same composition as that being tested, was included in the silk bag to augment and sustain ignition. A booster charge of 0.4 gram of finely ground propellant of the same composition as that being tested, was rolled into a paper cylinder and inserted in the igniter hole to form an ignition train between the ignition cartridge and the bag charge. Following this the ignition cartridge and end plug were inserted and the ignition cartridge fired. The output of the pressure gauge was recorded on the oscillograph. Paper speeds for various rounds ranged from 16 to 100 inches per second. Rounds used to determine the impetus were all temperature conditioned at +70°F for at least 4 hours. Rounds used to determine the burning rate were temperature conditioned at -65°F, +70°F, or +160°F for at least 4 hours.

Eight rounds of each propellant were fired to determine its impetus - two at a nominal maximum pressure of 2500 psi; two at 5000 psi; two at 7500 psi; and two at 10,000 psi. For each firing, the propellant was ground to pass U. S. sieve #30 or finer. As shown in Figure 3, P_{max} was determined by extrapolating the pressure-time trace back to a time corresponding to approximately $P_{max}/2$. Equation (8) was fitted to the data by least squares analysis to obtain the impetus and the covolume. The calculations were carried out on an IBM 7090 high speed digital computer.

Four rounds of each propellant were fired at each conditioning temperature to determine its burning rate at that temperature - two at a nominal maximum pressure of 5000 psi and two at 10,000 psi. The grain dimensions of each propellant were determined by measuring at least 10 grains with a micrometer and obtaining an average length and diameter for use in the calculations. In those cases in which the perforation diameter of the propellant grain was so small as to make measurement difficult, the manufacturers data for the nominal perforation diameter was used. For each firing, the propellant was loaded and fired in the "as received" condition. As shown in Figure 4, the pressure-time trace was divided into equal time intervals starting at an arbitrary zero time. The burning rate versus pressure was determined for each firing using equations (9), (11), (17) and (20). The calculations were carried out on an IBM 7090 high speed digital computer. The slope dP/dt was determined

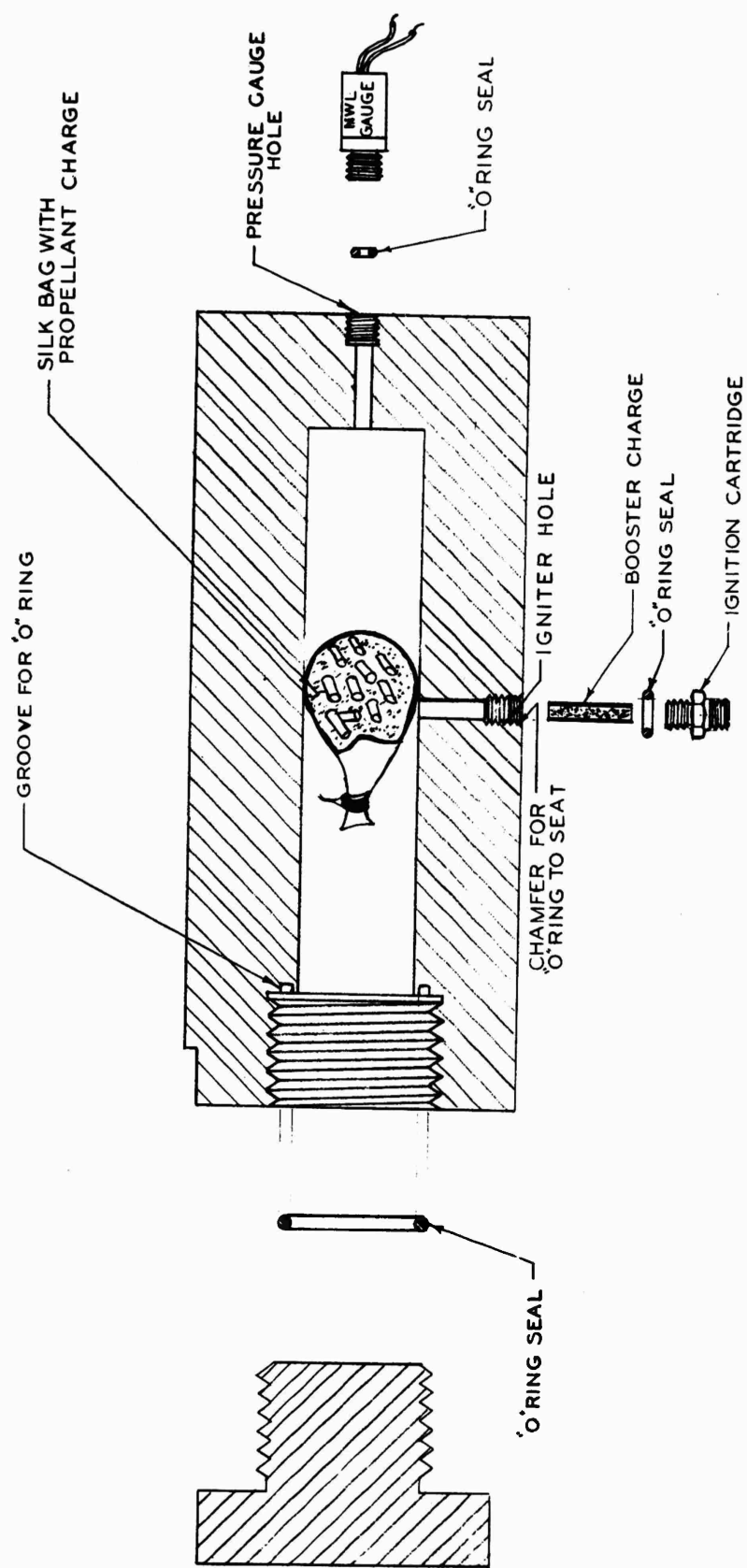


FIGURE 2: APPARATUS DIAGRAM -CLOSED VESSEL

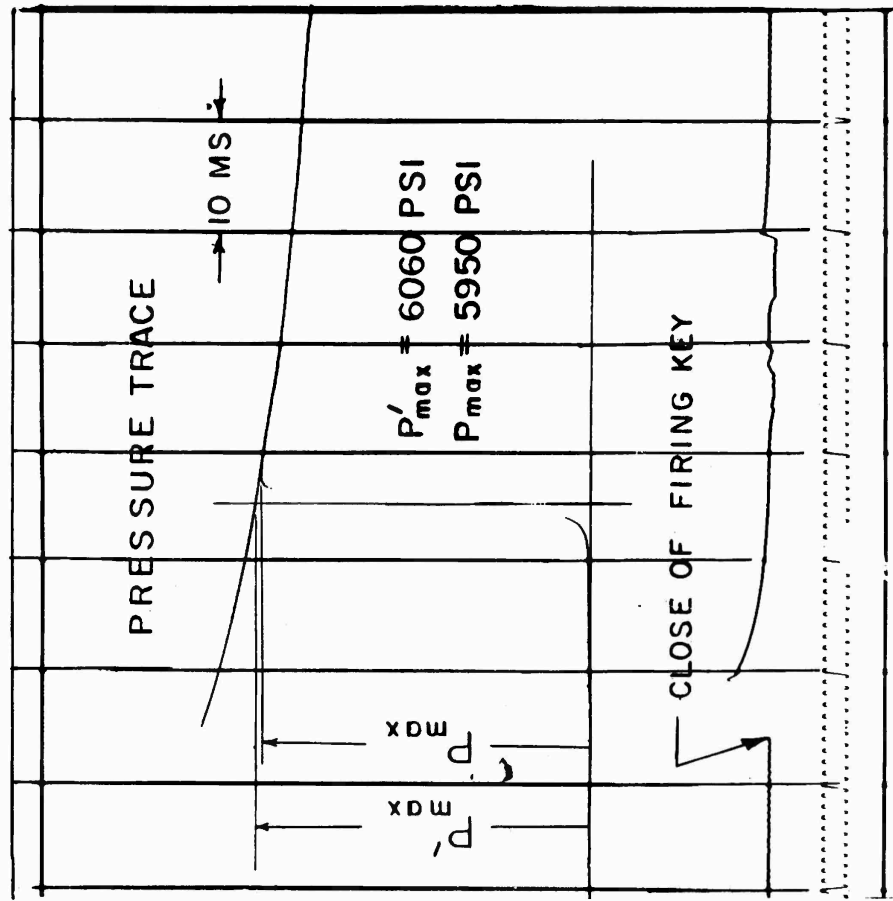
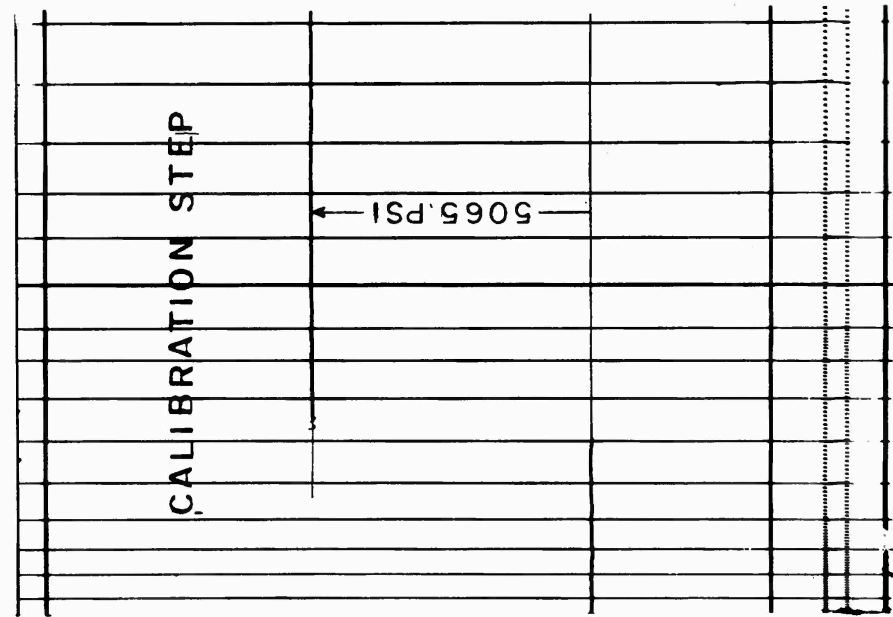


FIGURE 3: TYPICAL OSCILLOGRAPH RECORD
 for DETERMINING IMPETUS- HES 5250.96 RD 18 8-21-62

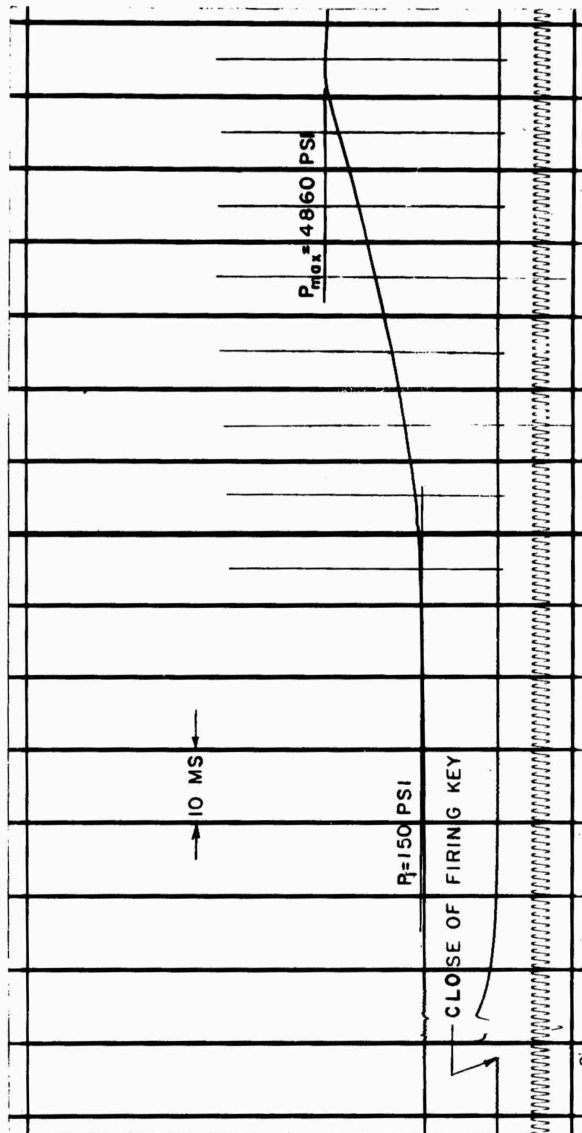
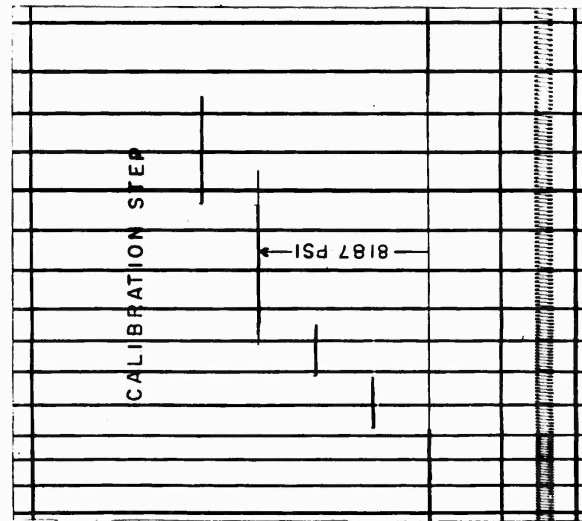


FIGURE 4: TYPICAL OSCILLOGRAPH RECORD
for DETERMINING BURNING RATE— HES 5250.96 RD 5 8-22-62

using the difference technique, whereby $\left(\frac{dP}{dt}\right)_{j+1/2}$ was approximated by $(P_{j+1} - P_j)/\Delta t$. The burning rate corresponding to this slope was then associated with the intermediate total pressure given by $(P_{j+1} + P_j)/2$. The partial pressures P and P_{\max} produced by the propellant burned were determined by subtracting the partial pressures P_i of the igniter charge and the air in the chamber. The partial pressure P_i was calculated using the known igniter charge weight and the impetus of the igniter material; in these cases the impetus of the propellant being tested.

III. Results -

The burning rate versus pressure was determined at each of three conditioning temperatures (-65°F, 70°F and 160°F) for 12 solid propellant samples. The impetus and covolume were determined at one conditioning temperature (70°F) for 13 propellant samples. Five of the samples (HES 5250.87, HES 5250.200, HES 5250.201, HES 5250.202, HES 5250.203) were identical in composition, notwithstanding manufacturing tolerances, differing only in granulation (size and shape) of the solid propellant.⁶ The propellant sample identified as "Unique" was received in a flake form of thin discs. The total burning time for this sample was less than 10 milliseconds when fired in the "as received" condition. Therefore, the "Unique" was not ground as were all other samples in the impetus firings. Due to the short burning time and corresponding steep pressure slope dP/dt , no attempt was made to determine the burning rate of "Unique".

Figure 3 is a typical example of a pressure-time oscillograph record used to determine impetus. Also depicted is the extrapolation of the pressure-time trace to obtain P'_{\max} . While P'_{\max} is the estimated adiabatic partial pressure of the propellant gases, it can be obtained directly from the record as shown. Since the zero of the pressure gauge is at one atmosphere, it does not sense the partial pressure of the air in the vessel at ignition. Hence, it is necessary to consider only the partial pressure produced by the ignition cartridge, but this is negligible compared to the total pressure, being less than 0.5% of the total pressure in each firing. For purposes of the impetus calculations, the mass of the booster charge is added to the mass of the

⁶Nominal chemical composition of the 13 propellant samples reported here are listed in Appendix B.

propellant to obtain the total propellant mass C_b . Hence, no correction is required for the pressure produced by the booster charge. Figure 1 is a typical example of a plot of $(V_o/C_b + 1/\rho)$ versus $1/P'_{max}$. Superimposed on the data points is the straight line obtained from the least squares analysis.

Figure 4 is a typical example of a pressure-time oscillograph record used to determine burning rate. Also depicted are the intervals at which the pressures were read and the pressure P_1 produced by the original gases at ignition. Figure 5 is a typical example of a plot of burning rate versus pressure for a conditioning temperature of 70°F. Superimposed on the data points is the straight line obtained from the least squares analysis. The end points of the solid line indicate the range of pressure over which the least squares analysis was made. The dotted line was fitted visually to the scattered points at low pressure. The significantly lower calculated values for burning rate and the scatter in the data at low pressures is attributed to incomplete ignition and the nonreproducibility of the ignition process. The rates indicated by the dotted line are not considered to be definitive, but may be useful in ballistic calculations where a method of approximating imperfect ignition is required. Data points indicated by an asterisk (*) were not included in the least squares analysis. These points correspond to the region of ignition and the region of burnout. It was assumed that some grains of the charge were ignited earlier in time than others and that some grains burned out earlier. If this was the case, equation (11), which relates the mass of propellant burned C to the distance l the burning surface has receded, would no longer be valid and calculated values for the burning rate could be expected to differ widely from the general trend of the burning rate curve as was the case in these experiments. Also in the case of multiperforated granulations, equation (11) is no longer valid after splintering.⁷ Hence, burning rate data occurring in the region after splintering were deleted from the results given below where applicable.

Figures 6 through 16 (see Appendix A) show the burning rates versus pressure at three conditioning temperatures (-65°F, 70°F and 160°F) for 12 propellant samples. The solid and dotted lines have the same significance as in Figure 5 except that the solid lines in Figures 6, 7, 16 and 17 were fitted visually to the data rather than

⁷Splintering is the time at which the walls of the perforations burn through leaving disjointed cylinders whose cross-sections are curvilinear triangles.

being obtained from least squares analyses. The data for these propellant samples (Arcite 433A, HES 5250.86, HES 6574.6 and IND 7191) was significantly nonlinear when plotted on logarithmic graph paper and could be more adequately represented by the curved lines shown. No attempt was made to obtain equations for these curves. The burning rate coefficients B and indices n , obtained from the least squares analyses, are listed in Table 1 (see Appendix A).

Table 2 (see Appendix A) lists the values of impetus and covolume obtained by least squares analysis for each of the propellant samples conditioned at 70°F. Also included are the density ρ and the nominal dimensions of the solid grain.

CONCLUDING REMARKS

The uniformity of the results which are obtainable by the methods described are indicated by the data presented for the several propellants. While the data for determining impetus are quite uniform, considerable scatter exists in the burning rate data. This closed vessel method of determining burning rate is relatively simple, but renders doubtful results in the region of ignition (usually below 30 bars), and results obtained in the latter stages of burning must be discarded for reasons noted above. The covolumes reported here may be less accurate than might have been obtained if the method were extended to higher pressures. However, there is no reason why the impetus, covolume, and burning rate could not be determined at higher pressures. For the work reported here, the limiting factor was the strength of the closed vessel (maximum working pressure: 10,000 psi). It is believed that propellant parameters can be determined with sufficient precision by the techniques described to have a high degree of predictive value when used in ballistic calculations involving cartridge actuated devices.

REFERENCES

- (a) Corner, J., "Theory of the Interior Ballistics of Guns", John Wiley and Sons, Incorporated, New York, New York, 1950
- (b) Hunt, Colonel F. R. W. (Chairman, Editorial Panel), "Internal Ballistics", His Majesty's Stationery Office, London, 1951
- (c) Pallington, Arnold O. and Weinstein, Murray, "Method of Calculation of Interior Ballistic Properties of Propellants from Closed Bomb Data", Picatinny Arsenal Technical Report PA 2005

APPENDIX A

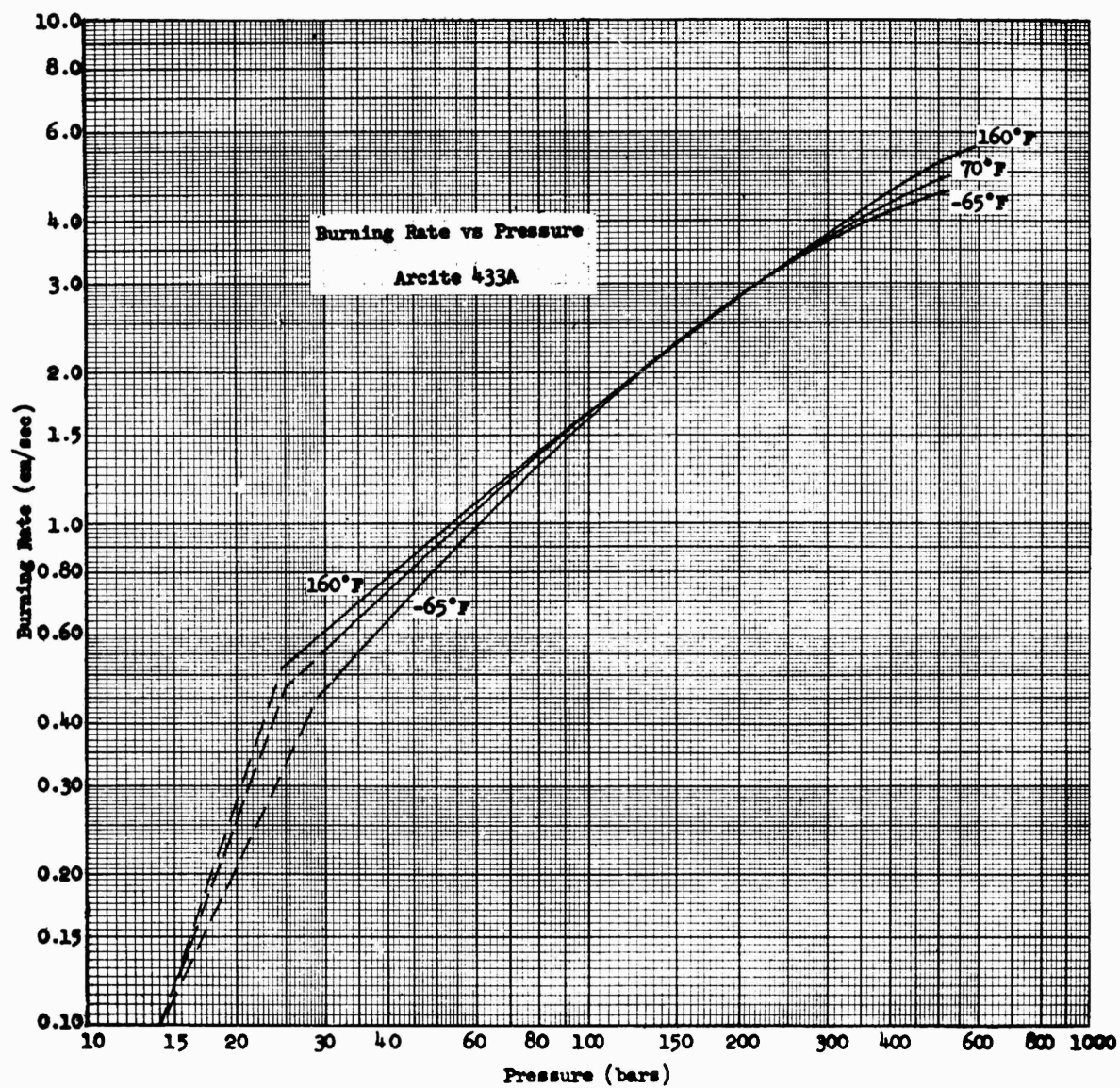


FIGURE 6: BURNING RATE - ARCITE 433A

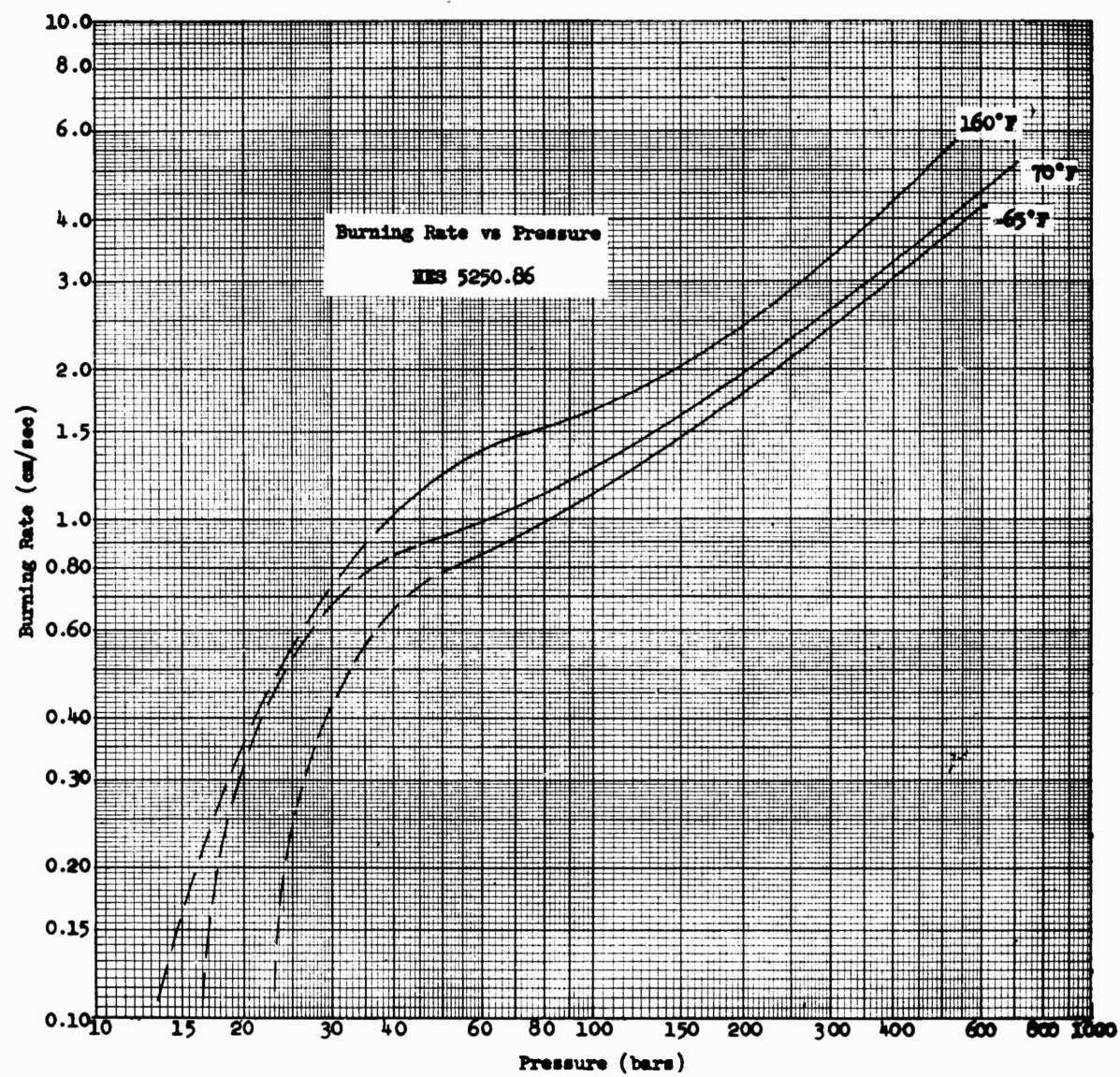


FIGURE 7: BURNING RATE - HES 5250.86

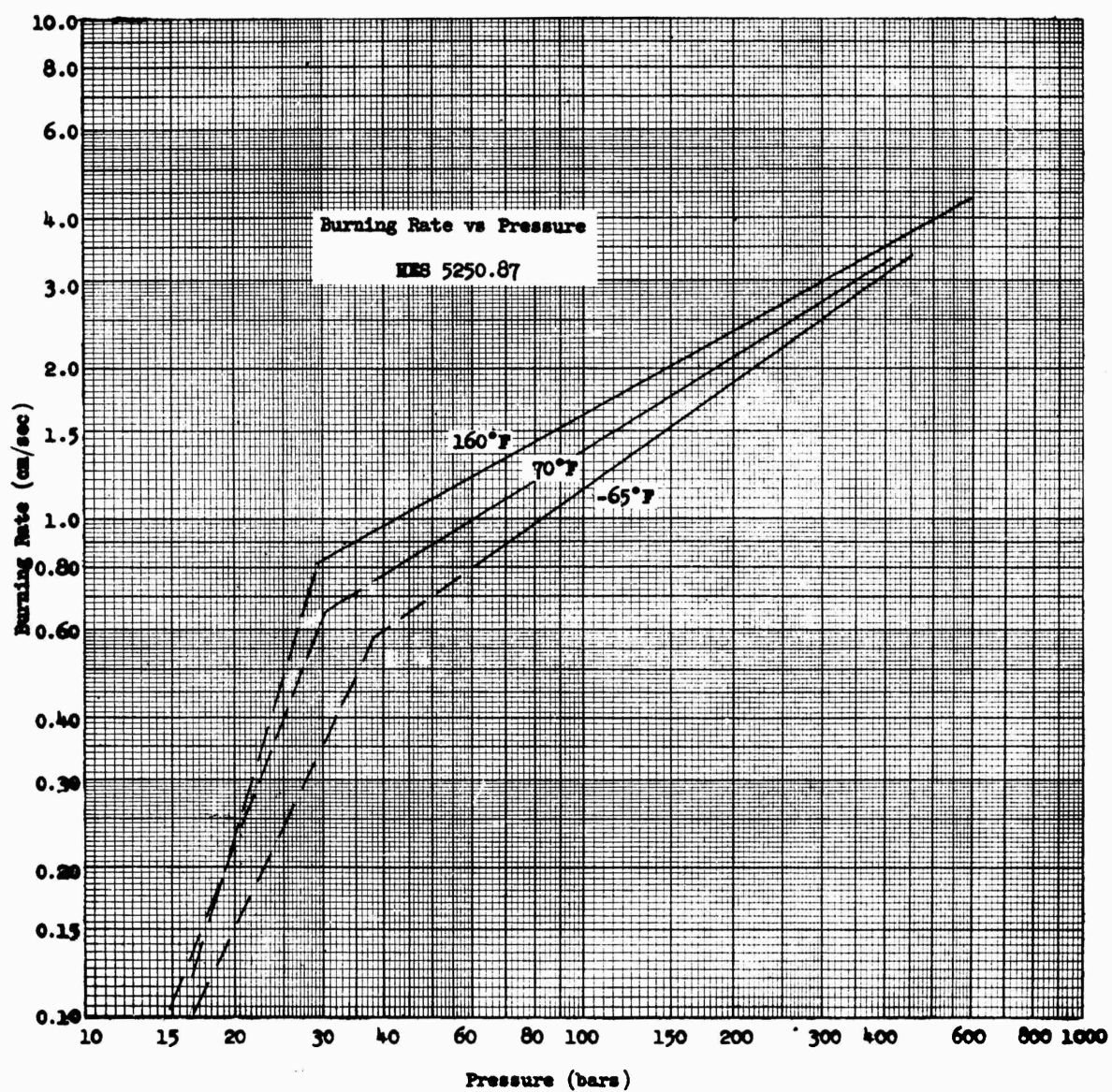


FIGURE 8: BURNING RATE - NES 5250.87

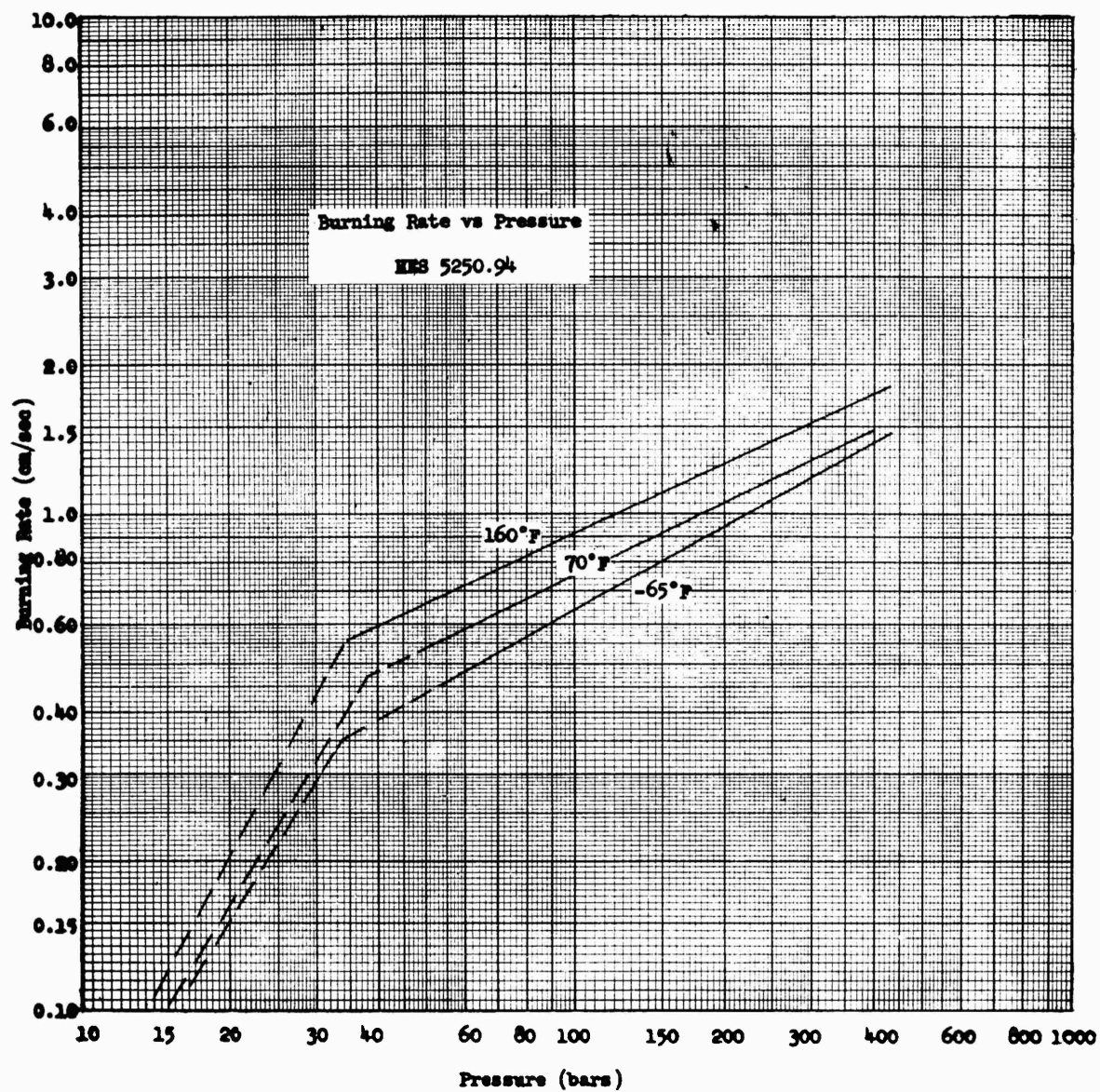


FIGURE 9: BURNING RATE - MKS 5250.94

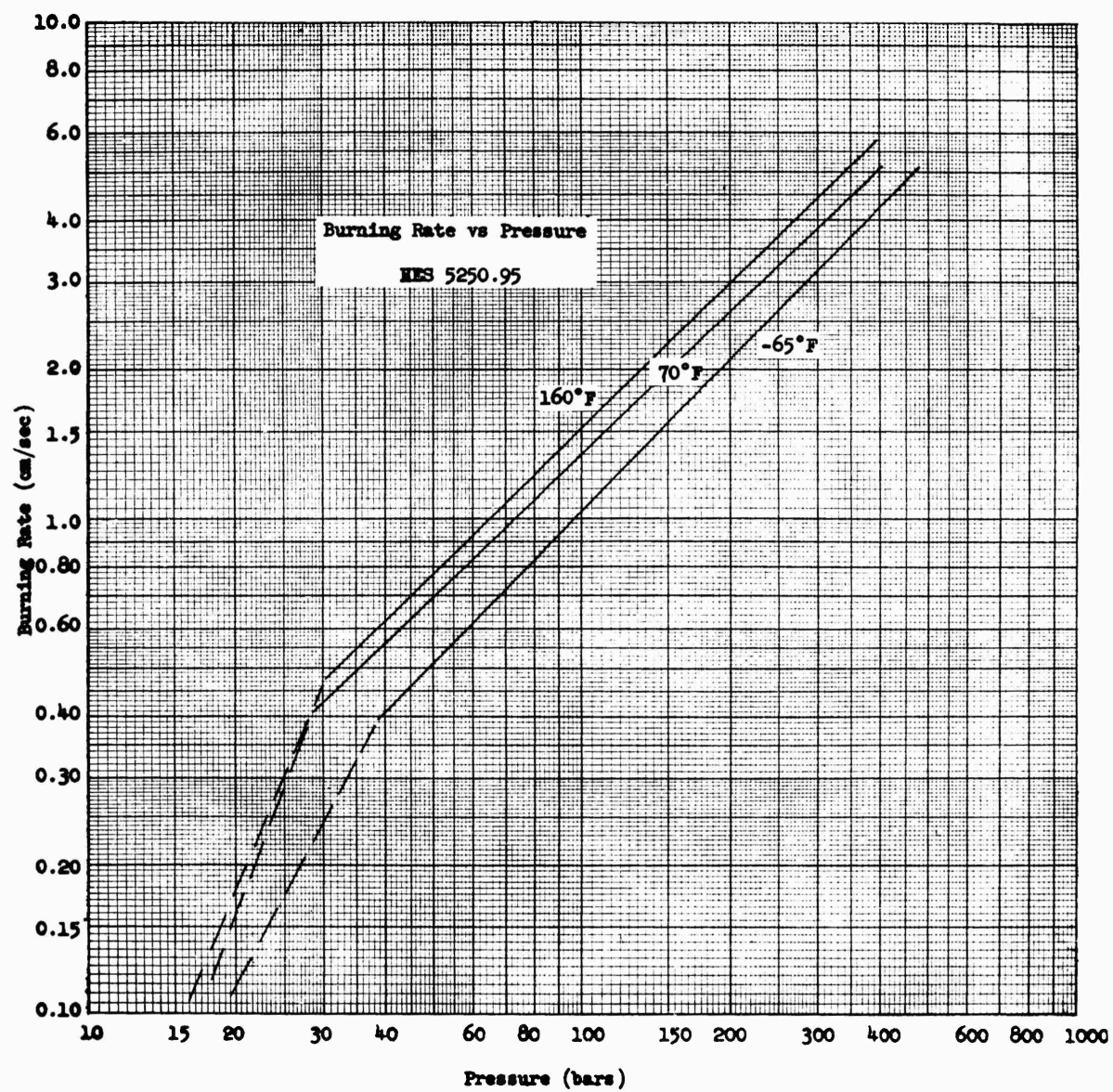


FIGURE 10: BURNING RATE - NES 5250.95

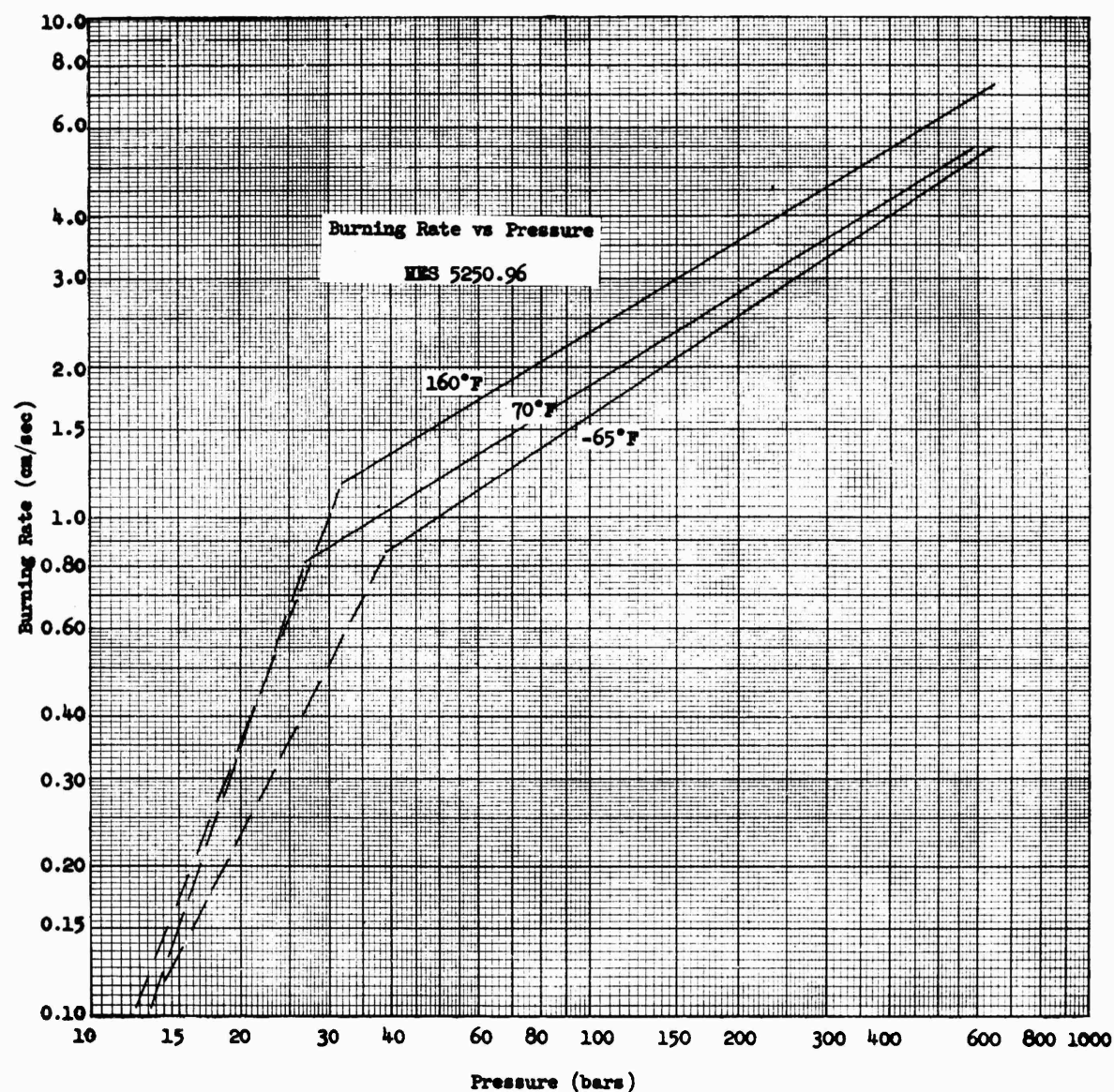


FIGURE 11: BURNING RATE - HES 5250.96

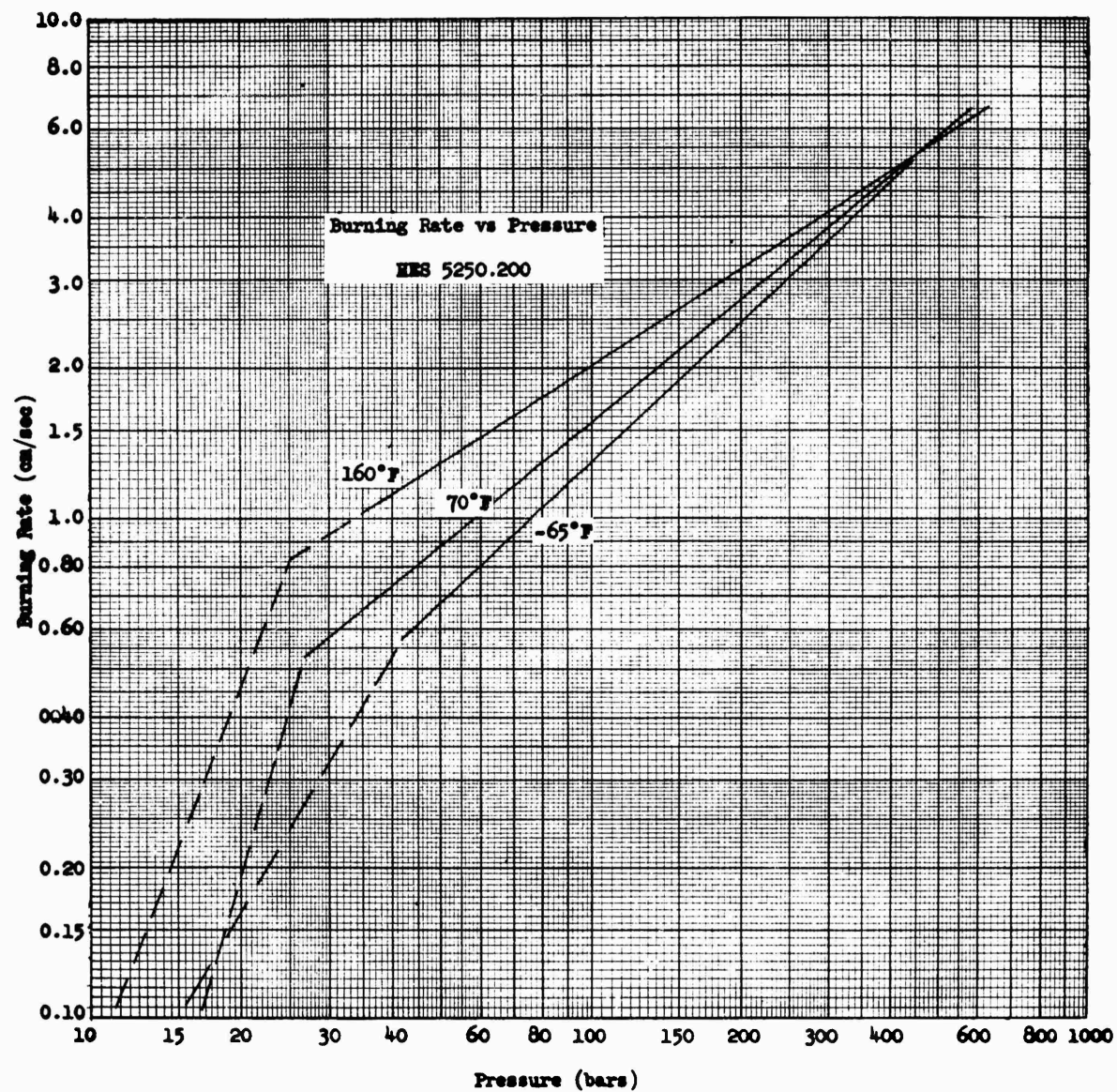


FIGURE 12: BURNING RATE - NES 5250.200

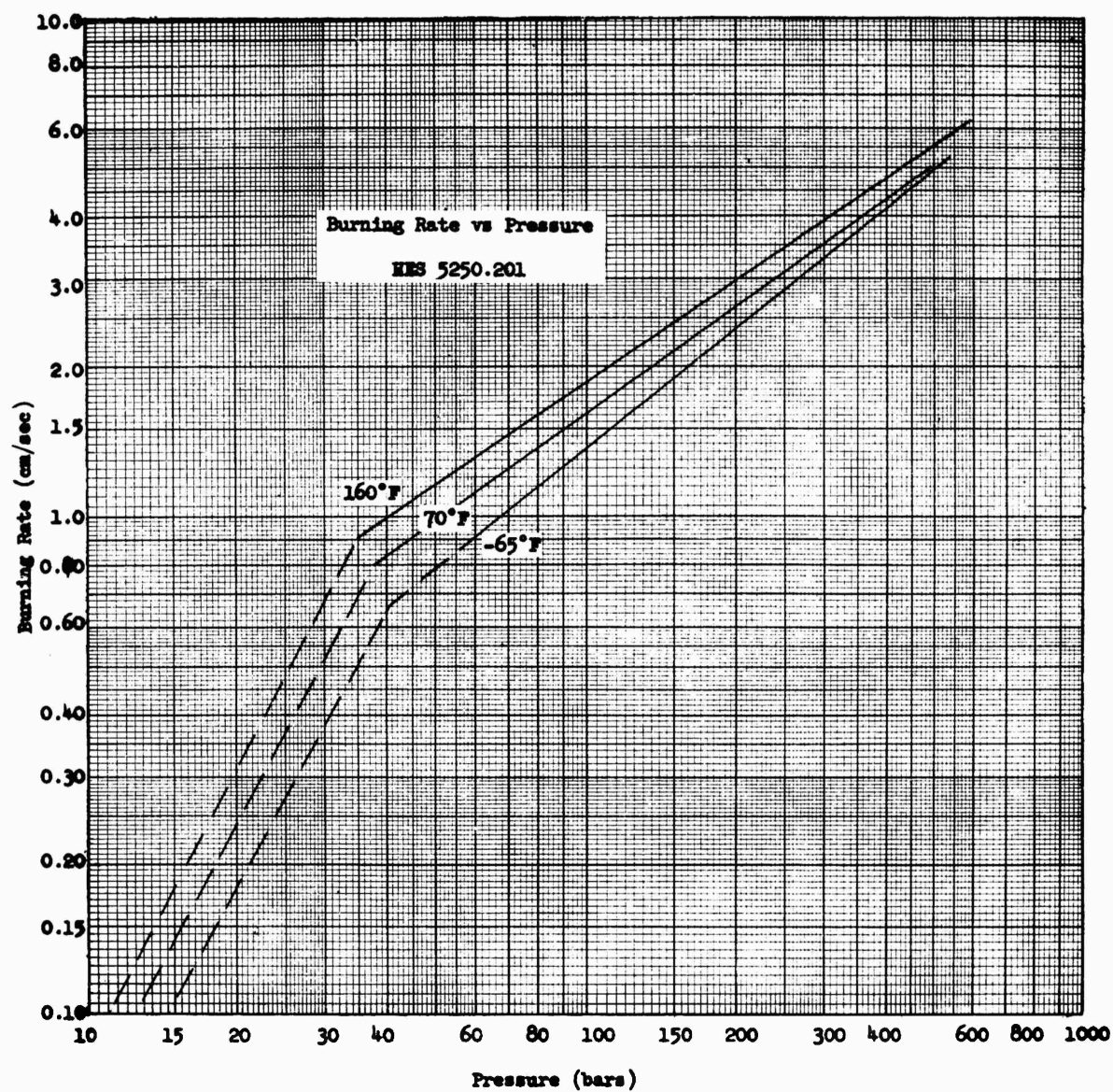


FIGURE 13: BURNING RATE - NES 5250.201

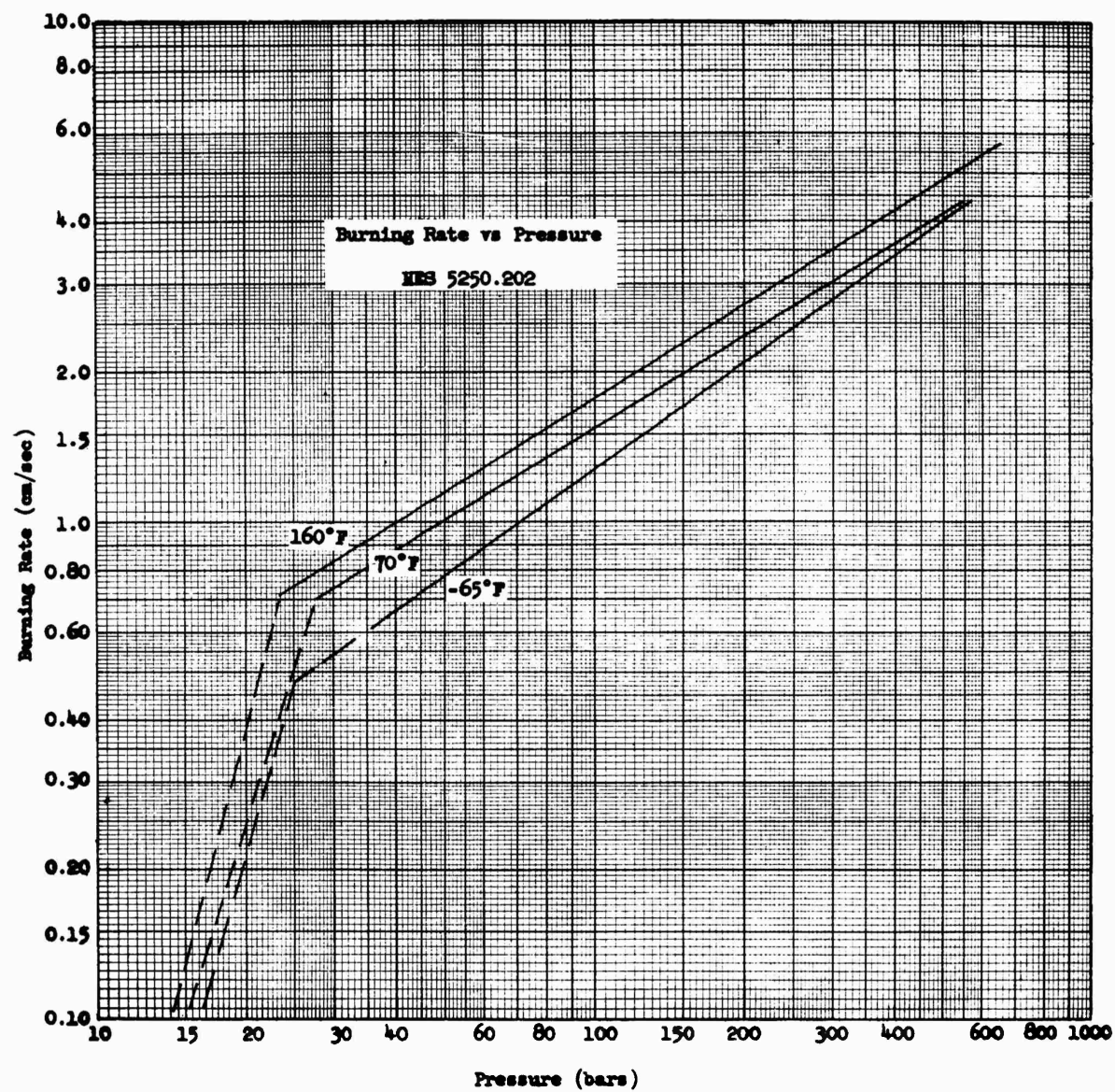


FIGURE 14: BURNING RATE - NES 5250.202

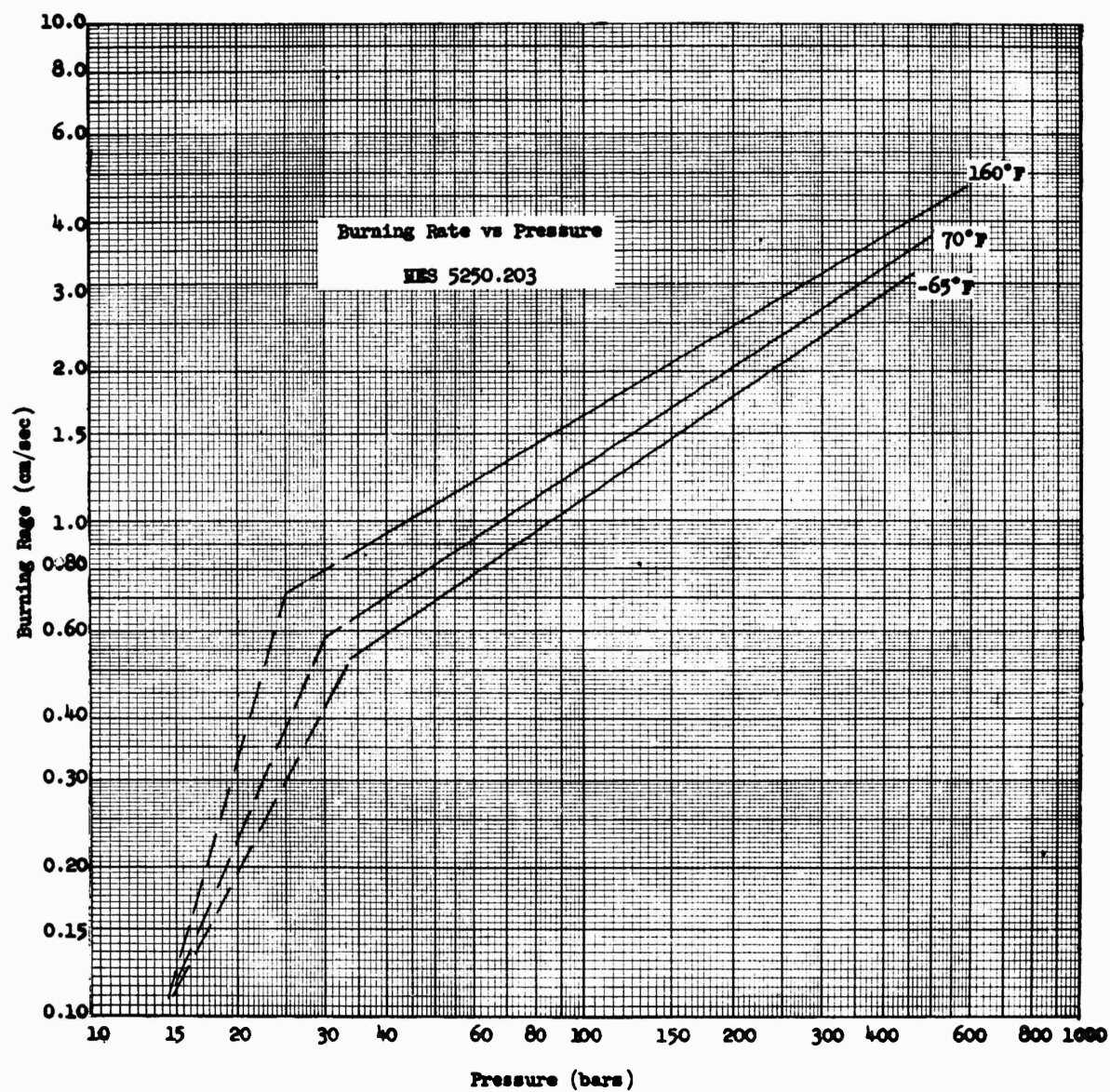


FIGURE 15: BURNING RATE - HES 5250.203

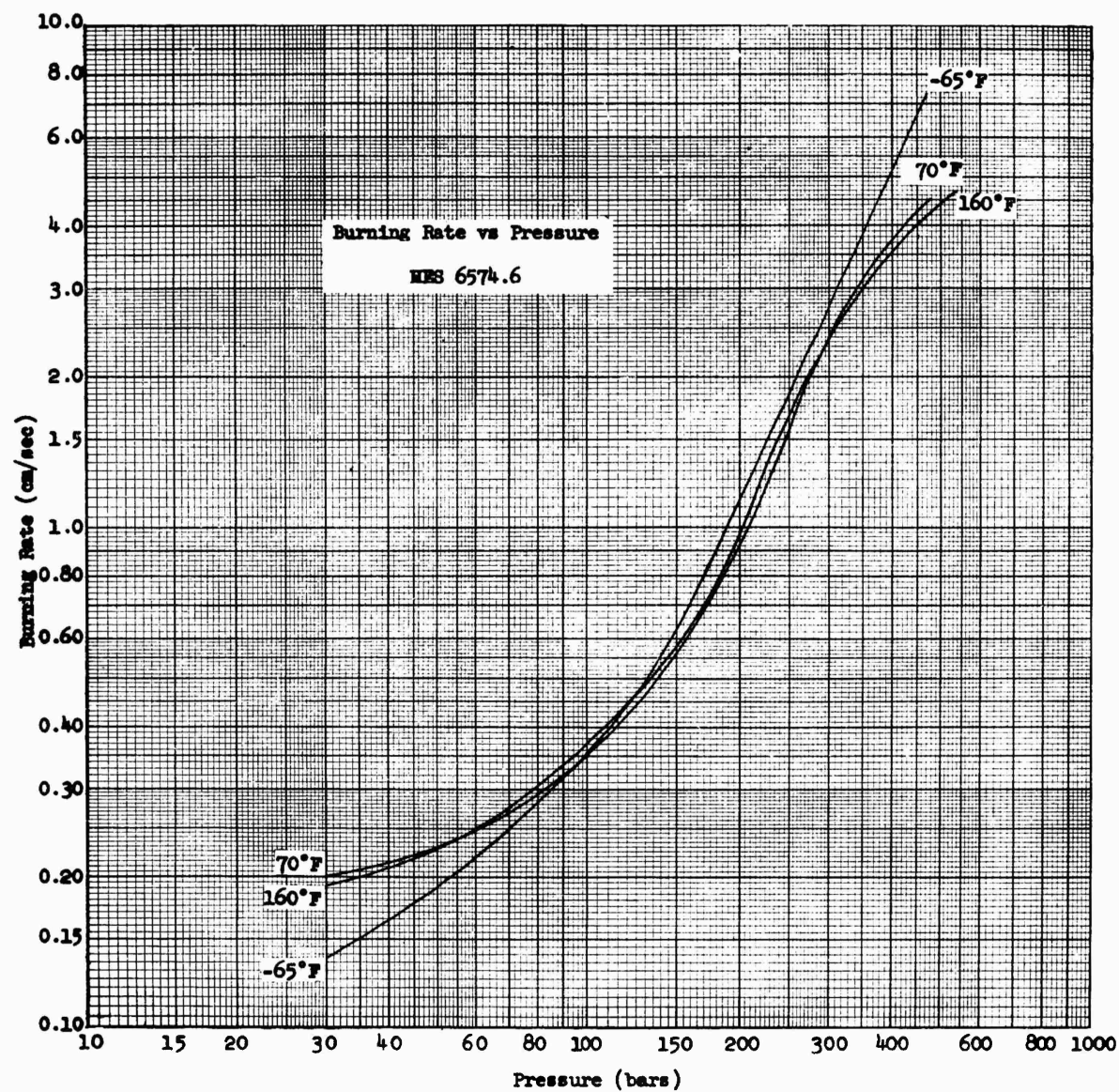


FIGURE 16: BURNING RATE - MES 6574.6

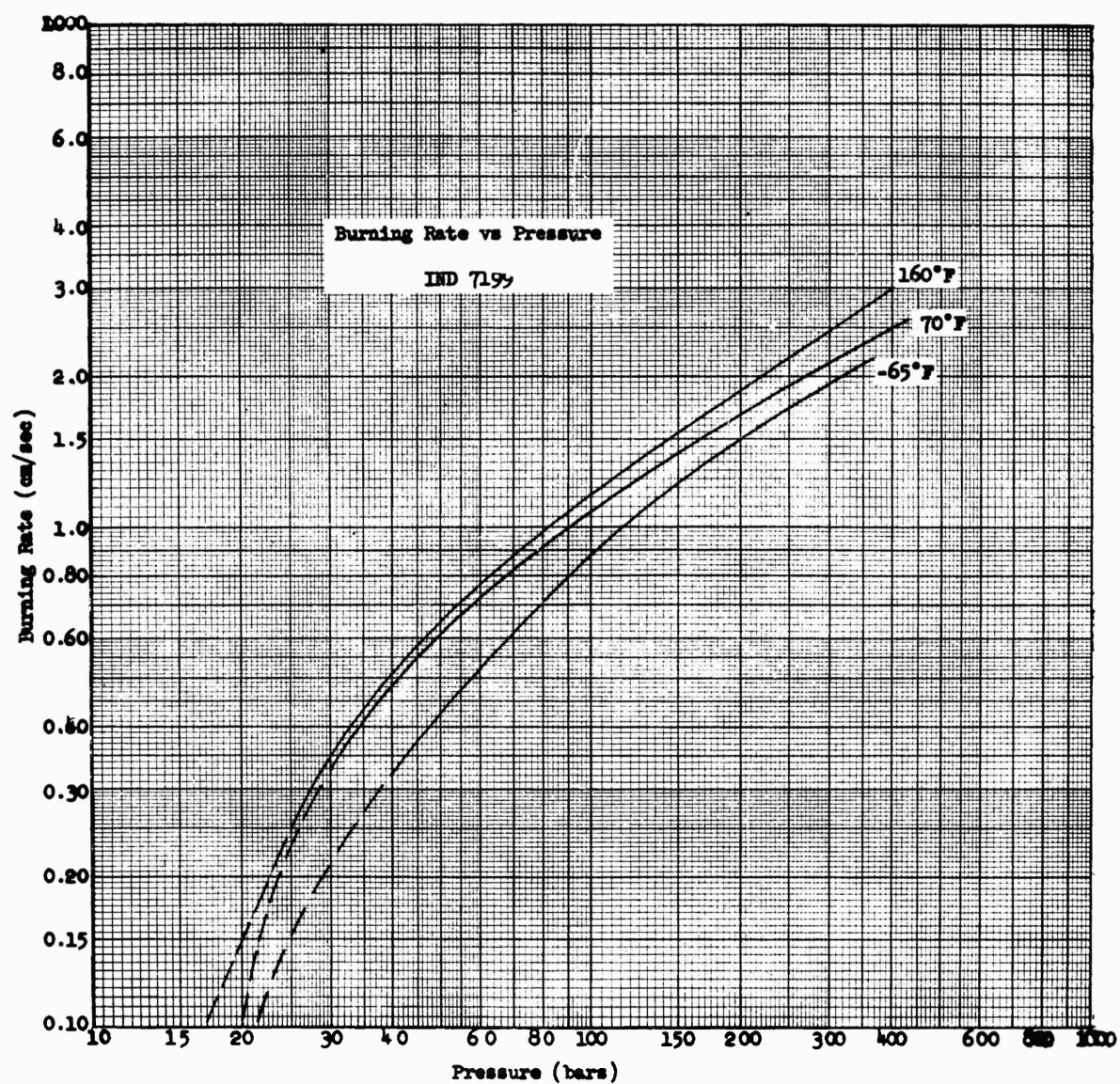


FIGURE 17: BURNING RATE - IND 7199

TABLE 1BURNING RATE COEFFICIENT B AND INDEX n - OBTAINED FROM LEAST SQUARES ANALYSIS

Propellant Designation	B (160°F)	n (160°F)	B (70°F)	n (70°F)	B (-65°F)	n (-65°F)
HES 5250.87	0.5467 X 10 ⁻⁴	0.5590	0.1398 X 10 ⁻⁴	0.6239	0.2372 X 10 ⁻⁵	0.7106
HES 5250.94	0.1655 X 10 ⁻³	0.4679	0.9819 X 10 ⁻⁴	0.4859	0.2194 X 10 ⁻⁴	0.5584
HES 5250.95	0.2521 X 10 ⁻⁷	0.9725	0.3031 X 10 ⁻⁷	0.9560	0.7015 X 10 ⁻⁸	1.0214
HES 5250.96	0.3213 X 10 ⁻⁴	0.6079	0.2130 X 10 ⁻⁴	0.6171	0.7185 X 10 ⁻⁵	0.6687
HES 5250.200	0.1420 X 10 ⁻⁴	0.6443	0.4446 X 10 ⁻⁶	0.8180	0.4707 X 10 ⁻⁷	0.9300
HES 5250.201	0.6859 X 10 ⁻⁵	0.6790	0.3161 X 10 ⁻⁵	0.7133	0.5428 X 10 ⁻⁶	0.8003
HES 5250.202	0.1753 X 10 ⁻⁴	0.6255	0.1917 X 10 ⁻⁴	0.6132	0.2402 X 10 ⁻⁵	0.7157
HES 5250.203	0.2624 X 10 ⁻⁴	0.5992	0.6577 X 10 ⁻⁵	0.6613	0.3844 X 10 ⁻⁵	0.6824

TABLE 2
PROPELLANT DATA

PROPELLANT DESIGNATION	DENSITY- ρ (gm/cm^3)	VOLUME- V (cm^3/gm)	FORM FUNCTION COEFFICIENTS			DISTANCE SURFACE HAS RECEDED AT BURNOUT- J_b (cm)	NOMINAL DIMENSIONS ¹		
			a_1 (cm^{-1})	a_2 (cm^{-2})	a_3 (cm^{-3})		O D (cm)	I D ² (cm)	LENGTH (cm)
ARCITE 433A	0.8550×10^{10}	0.332	4.58668	-1.23042	0	0.23288	1.302	0.3705 (1)	6.980
HES 5250.86	0.9662×10^{10}	0.890	9.71950	-31.48910	34.0055	0.30750	0.615	-- (0)	0.622
HES 5250.87	0.9724×10^{10}	1.542	12.01290	0.24142	-183.4040	0.07825	0.678	0.0406 (7)	0.584
HES 5250.94	0.8540×10^{10}	1.818	16.99540	-40.70010	0	0.07087	0.292	0.0086 (1)	0.693
HES 5250.95	1.0584×10^{10}	1.439	20.06012	81.89630	-727.2780	0.04490	0.401	0.0279 (7)	0.424
HES 5250.96	1.1683×10^{10}	0.615	8.83410	-11.05610	0	0.13652	0.734	0.1879 (1)	1.325
HES 5250.200	1.1243×10^{10}	0.986	36.39135	-88.09330	0	0.02960	0.144	0.0256 (1)	0.767
HES 5250.201	1.0399×10^{10}	0.804	21.39270	-31.85570	0	0.05055	0.239	0.0368 (1)	1.242
HES 5250.202	1.0081×10^{10}	1.484	11.28614	-10.80270	0	0.09775	0.424	0.0330 (1)	1.894
HES 5250.203	1.0129×10^{10}	1.044	6.20201	-4.67089	0	0.18780	0.858	0.1068 (1)	2.280
HES 6574.6	0.9623×10^{10}	3.022	10.99938	-10.70190	0	0.10080	0.454	0.0508 (1)	1.854
IND 7199	0.9304	1.219	4.70375	7.45275	-4.9066	0.17133	1.626	0.1422 (7)	3.912
UNIQUE	1.1157×10^{10}	1.873	-	-	-	-	≈ 0.150	- (0)	≈ 0.020

¹ All samples are right circular cylinders. Perforations are axial.² Number in parenthesis indicates number of perforations.

APPENDIX B

COMPOSITION OF PROPELLANT SAMPLES

<u>Composition</u>	<u>Weight (g)</u>
ARCITE 433A:	
Ammonium perchlorate	38.55
Potassium perchlorate	38.55
Polyvinyl chloride	9.97
Diethyl adipate	10.20
Copper chromite	0.97
British wetting agent	0.25
Carbon black	0.05
Aluminum	0.99
Ferro 1203	0.47
	<u>100.00</u>
HES 5250.86:	
Nitrocellulose (13.25N)	69.35
Nitroglycerine	20.00
Centralite	6.50
Barium Nitrate	1.00
Potassium Nitrate	1.00
Graphite	0.20
	<u>100.00</u>
HES 5250.87, .200, .201, .202, .203	
Nitrocellulose (13.25N)	71.30
Nitroglycerine	20.00
Centralite	6.50
Barium Nitrate	1.00
Potassium Nitrate	1.00
Graphite	0.20
	<u>100.00</u>
HES 5250.94	
Nitrocellulose (13.25N)	58.50
Nitroglycerine	22.50
Ethyl Centralite	8.00
Triacetin	8.00
Dinitrotoluene	2.50
Lead Stearate	0.50
	<u>100.00</u>

COMPOSITION OF PROPELLANT SAMPLES (Continued)

<u>Composition</u>	<u>Weight (%)</u>
HES 5250.95	
Nitrocellulose (13.25N)	78.00
Nitroglycerine	20.00
Potassium Sulphate	1.00
Graphite	0.25
Diphenylamine	<u>0.75</u>
	100.00
HES 5250.96	
Nitrocellulose (13.25N)	76.85
Nitroglycerine	20.00
Ethyl Centralite	0.65
Potassium Nitrate	0.80
Barium Nitrate	1.50
Graphite	<u>0.20</u>
	100.00
HES 6574.6	
This is an RDX base propellant. The exact composition is not available for publication.	
IND 7199:	
Nitrocellulose (13.16N)	86.67
Diphenylamine	0.86
Dinitrotoluene	9.59
Dibutylphthalate	<u>2.88</u>
	100.00
Unique:	
Nitrocellulose	59.70
Nitroglycerine	39.00
Centralite	<u>1.30</u>
	100.00

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Forces	FORC	Calculation	COMA
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Method	METD	Cartridges	CART
Closed	CLOX	Actuated	ACTA
Vessel	VESL	Devices	DEVI
Techniques	TECN	Volume	VOLU
Burning	BURN		
Gases	GASE		

<p>Naval Weapons Laboratory, Dahlgren, Virginia. (NWL Report No. 1872) MEASUREMENT OF THE IMPETUS, COVOLUME, AND BURNING RATE OF SOLID PROPELLANTS, by J. M. Massey. 31 July 1963. 13 p., 17 figs., 2 tables.</p> <p>UNCLASSIFIED</p> <p>A method, using closed vessel techniques, for determining the impetus (force constant), covolume, and burning rate of solid propel- lant is described. Data obtained by this method are presented for thirteen solid pro- pellants.</p>	<p>1. Solid propellants - Burning characteristics I. Massey, J. M.</p> <p>Task: RMO-33-020/210-1/ FO08-11-001 UNCLASSIFIED</p>	<p>Naval Weapons Laboratory, Dahlgren, Virginia. (NWL Report No. 1872) MEASUREMENT OF THE IMPETUS, COVOLUME, AND BURNING RATE OF SOLID PROPELLANTS, by J. M. Massey. 31 July 1963. 13 p., 17 figs., 2 tables.</p> <p>UNCLASSIFIED</p> <p>A method, using closed vessel techniques, for determining the impetus (force constant), covolume, and burning rate of solid propel- lant is described. Data obtained by this method are presented for thirteen solid pro- pellants.</p>	<p>1. Solid propellants - Burning characteristics I. Massey, J. M.</p> <p>Task: RMO-33-020/210-1/ FO08-11-001 UNCLASSIFIED</p>
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